AD-A062 566 DUKE UNIV DURHAM N C DEPT OF CIVIL ENGINEERING F/G 11/4
FATIGUE RESISTANCE CRITERIA FOR LAMINATED COMPOSITE STRUCTURES.(U)
OCT 78 G J DVORAK DAHC04-75-G-0131
UNCLASSIFIED SOLID MECHANICS SER-13 ARO-12825.1-E NL

1 OF 1
AD A062566

END
DATE FILMED
3-79
DDC

School of ENGINEERING DUKE UNIVERSITY

Solid Mechanics Series No. 13

(12)

FATIGUE RESISTANCE CRITERIA FOR LAMINATED COMPOSITE STRUCTURES

Final Report
Period: April 1, 1975 - June 15, 1978

by

GEORGE J. DVORAK

October, 1978
U.S. ARMY RESEARCH OFFICE
Grants DAHC04-75-G-0131; 77-G-0113
Department of Civil Engineering
Duke University, Durham, N.C.

Approved for public release; Distribution Unlimited

15 DAHCØ4-75-G-Ø131, DAHCØ4-77-G-Ø113

Solid Mechanics Series No. 13

6 FATIGUE RESISTANCE CRITERIA FOR

LAMINATED COMPOSITE STRUCTURES.

18 ARO 19 12825.1-E

9 Final Report, 1 Apr 75-15 Jun 78,

Period: April 1, 1975 - June 15, 1978

by

10 George J. Dvorak

14 SOLID MECHANICS SER-13

12 12 p.

11 October, 1978

U.S. ARMY RESEARCH OFFICE

Grants DAHC04-75-G-0131; 77-G-0113

Department of Civil Engineering

Duke University, Durham, N.C.

403 770

Approved for public release; Distribution Unlimited

403 770

SUMMARY

The purpose of the work supported by this grant was to investigate criteria for prevention of fatigue damage in metal matrix composite laminates. The approach to this problem was based on an earlier observation that in as-fabricated unidirectional composites with elastic-brittle fibers and soft elastic-plastic matrices fatigue failure can be prevented if the composite shakes down during cyclic loading. Accordingly, the objective of the research was to develop a theoretical background in plasticity of composite laminates which could be used to evaluate shakedown conditions for laminated structures.

The first part of the research work was concerned with completion of a plasticity theory for axisymmetric deformation of unidirectional composites under mechanical and thermal loads. A modified self-consistent scheme and other models was used to evaluate the elastic-plastic response of the composite. The results were applied to heat-treatment problems and to evaluation of residual microstresses in heat-treated materials.

The second part of the research work was directed at the development of a plasticity theory for fibrous laminates. The objective was to construct a phenomenological constitutive relation suitable for use in numerical solutions of geometrically complex problems in laminated structures. Attempts to find such a relation were made with several microstructural models of a composite lamina. Two different models were finally selected, one of them was used in a finite-element program. Certain problems involving localized yielding at holes in laminated plates were solved.

The essential conclusion derived from this work is that the fiber reinforcement strengthens the metal matrix considerably against ultimate failure, but it does not expand significantly the elastic deformation range of the matrix in the overall stress space. Therefore, the advantage derived from fiber reinforcement of metal matrices can be utilized only in the elastic-plastic deformation range of the composite. This opens the possibility of repeated cyclic plastic straining of the matrix in dynamic loading situations, and the prospect of low-cycle fatigue failure if the loading range is not limited by the requirement that the matrix must shake down and thus resume an elastic deformation mode.

1. AXISYMMETRIC PLASTIC DEFORMATION OF UNIDIRECTIONAL COMPOSITES

The results of this part of the research effort have been reported in References (1) to (4). An analytical procedure was developed for evaluation of local microstresses and of the overall elastic-plastic response of a composite cylinder consisting of a circular elastic fiber surrounded by a thick layer of an elastic-plastic matrix. Axisymmetric mechanical and uniform thermal loads were considered. This procedure leads to a numerical scheme which makes it possible to solve the composite cylinder problem without the use of the finite element method. An application of the procedure to evaluation of residual microstresses in heat-treated composites was made in Reference (2). A satisfactory agreement between the calculated results and available experimental results was obtained.

References (3) and (4) describe an extension of results obtained for the composite cyclinder model to macroscopic behavior of unidirectional composites. This was accomplished with a modified self-consistent model, in which the composite cylinder was regarded as a modified fiber inclusion containing a part of the elastic-plastic matrix. This modification was made to account for the nonuniform local plastic deformation in the matrix adjacent to the fiber, which would be neglected in the usual self-consistent approximation.

The results of the self-consistent calculations were summarized in Reference (4). It was shown that the incremental elastic-plastic formulation of the axisymmetric problem is quite analogous to the well-known elastic case, indeed, it was possible to derive an elastic-plastic analog to the connections between axisymmetric elastic moduli and thermal coefficients of a unidirectional composite. As a consequence, many closed-form results were obtained, and certain solutions of incremental loading problems were constructed without recourse to a numerical calculation. The treatment of the axisymmetric problem included the application of thermal loading, and the effect of temperature dependence of the matrix yield stress.

The results obtained from the self-consistent calculations permitted to make a comparison between the standard self-consistent model, the modified self-consistent model, and the composite cylinder model described in References (1) and (2). It was concluded that in axisymmetric problems with mechanical loading one can obtain similar overall response with all these models, and that the self-consistent model may be preferable in such problems because of its simplicity. In problems involving thermal loading, and also where microstresses are of interest, one should prefer the composite cylinder model and avoid the self-consistent model because it gives rather misleading results. The modified self-consistent model and the composite cylinder model perform well under all circumstances, with minor differences in results. Since the composite cylinder model is simpler to use, it may be preferable in calculations.

2. GENERAL ELASTIC-PLASTIC DEFORMATION OF UNIDIRECTIONAL COMPOSITES

In addition to the axisymmetric results described in Section 1, Reference (4) reports results of exploratory calculations in which the unmodified self-consistent model was used to evaluate initial yield conditions of the unidirectional composite under general non-symmetric loading. The results were quite disappointing, for certain loading directions, e.g. for pure longitudinal shear, one obtained overall initial yield stresses which exceeded in magnitude the upper bound on the limit load for a unidirectional lamina. These results clearly disqualified the self-consistent model from consideration in development of a general elastic-plastic theory. The shortcomings of the self-consistent scheme follow from the fact that the strain fields in the inclusions are uniform, and thus the model cannot account for localized nonuniform deformation which dominates the plastic response of fibrous composites. The modified model rectifies these deficiencies in principle, but simple nonsymmetric solutions for the composite cylinder are not available, and that makes the use of the modified scheme impractical.

In fact, an examination of the utility of material models that have been used with considerable success in formulations of elastic and linear viscoelastic constitutive relations for fiber reinforced materials reveals that these models cannot be used in plasticity, and that it is necessary to use rather simple material models which represent only the essential aspects of the elastic-plastic behavior.

This is discussed in Reference (5), which also presents a simple model for an elastic-plastic lamina. It consists of a matrix unidirectionally reinforced with continuous elastic fibers. Each of the fibers is assumed to be of very small diameter, so that although the fibers occupy a finite volume fraction of the composite, they do not interfere with matrix deformation in the transverse plane. The matrix is an elastic-plastic solid, with known hardening and flow rules, which can be quite general. Similar models have been used by other authors in descriptions of nonlinear viscoelastic behavior of fibrous composites.

3. ELASTIC-PLASTIC BEHAVIOR OF COMPOSITE LAMINATES

The hardening and flow rules developed with the model of elastic-plastic lamina discussed in Section 2 was applied to plastic deformation problems in laminated plates. One part of these results has been described in (5), other parts will be reported in the near future.

Reference (5) describes the comparison of calculated results with experiments. A group of experimental results was obtained for a laminated B-Al plate specimens tested in uniaxial tension. A number of different layups was tested, stress-strain curves and ratios of axial to transverse strains were measured in simple tension tests. In the calculations it was possible to derive matrix properties from one set of tests and then simulate the experimental results obtained for other sets of tests. These derived matrix properties were different from those measured on the bulk matrix. The numerical calculations were found to be in good agreement with experimental results.

The elastic-plastic constitutive equations have been used in a finite element computer program, which was developed from an existing program, ELAS65, created under earlier Army grants. The program can solve any three-dimensional problem for a laminated medium, each unidirectional lamina must be represented by at least one layer of elements.

The problems solved so far with this program include a more exact simulation of the experiments mentioned earlier, in which a finite element model of the actual specimen geometry has been employed. This calculation gave better agreement with experimental results.

Another problem solved with the program pertains to the development of plastic flow in a laminated (0 ± 90) B-Al plate with a round hole, loaded by simple tension. The results of this study indicate that the laminated plate starts to yield at about the same stress level as a similar aluminum plate without reinforcement. Plastic flow spreads quite rapidly as the load increases, particularly in the 90 degree layer. The failure strength of the reinforced plate is much higher than that of an unreinforced one, but this strength advantage can be utilized only in the plastic deformation range of the laminate. Similar results are expected for other laminate layups.

The conclusion which appears to emerge from these initial results is that the fiber reinforcement does not strengthen the matrix against yielding, it does strengthen it only against failure. As a consequence, the useful loading range of a composite laminate coincides with the plastic flow range. This is an unusual feature of laminate behavior which does not seem to be present in other structural materials. One obvious consequence is the existence of permanent deformations in laminated parts. Other consequences may include the possibility of cyclic plastic straining in the matrix which may lead to low cycle fatigue failure of the material. In any event, it is clear that further studies of elastic-plastic behavior of metal matrix laminates are necessary for further understanding of the mechanical behavior of these materials.

TABLE 1

List of Papers and Reports Prepared Under Project 12825-E

1. G. J. Dvorak, and M.S.M. Rao, "Axisymmetric Plasticity Theory of Fibrous Composites", International Journal of Engineering Science, Vol. 14, pp. 361-373, 1976.

2. G. J. Dvorak, and M.S.M. Rao, "Thermal Stresses in Heat-Treated Fibrous Composites", Journal of Applied Mechanics, Vol. 98, pp. 619-624, 1976.

3. J. Q. Tarn, "Elastic-Plastic Behavior of Unidirectional Composites" Ph.D. Dissertation, Duke University, September, 1976.

4. G. J. Dvorak, and Y.A. Bahei-El-Din, "Elastic-Plastic Behavior of Fibrous Composites", Journal of the Mechanics and Physics of Solids, Vol. 26, No. 6, 1978.

5. G. J. Dvorak, and Y.A. Bahei-El-Din, "Plasticity of Composite Laminates", Proc. Research Workshop on Mechanics of Composite Materials, Duke University, October, 1978.

List of Scientific Personnel and Degrees Earned

Dr. G.J. Dvorak	- Principal Investigator
Mr. Y.A. Bahei-El-Din	- Research Assistant, Completed a major part of his Ph.D. program while supported by this grant.
Mr. William Steven Johnson	- Research Assistant
Ms. Stephanie Kunz	- Research Assistant
Mr. J.Q. Tarn	- Research Assistant, Ph.D., September 1976, supported by this grant.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Fatigue Resistance Criteria for Laminated Composite Structures		5. TYPE OF REPORT & PERIOD COVERED FINAL 4/1/75 to 6/15/78
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George J. Dvorak		8. CONTRACT OR GRANT NUMBER(s) DAHC04-75-G-0131; 77-G-0113
9. PERFORMING ORGANIZATION NAME AND ADDRESS Duke University Durham, North Carolina 27706		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE October, 1978
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Composite Materials
Metal Matrices
Fibers
Fatigue

This work investigated

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of the work supported by this grant was to investigate criteria for prevention of fatigue damage in metal matrix composite laminates. The approach to this problem was based on an earlier observation that in as-fabricated unidirectional composites with elastic-brittle fibers and soft elastic-plastic matrices, fatigue failure can be prevented if the composite shakes down during cyclic loading. Accordingly, the objective of the research was to develop a theoretical background in plasticity of composite laminates which could be used to evaluate shakedown conditions for laminated structures. (over)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(9)

Cont

20. First, a plasticity theory was developed,

The first part of the research work was concerned with completion of a plasticity theory for axisymmetric deformation of unidirectional composites under mechanical and thermal loads. A modified self-consistent scheme and other models was used to evaluate the elastic-plastic response of the composite. The results were applied to heat-treatment problems and to evaluation of residual microstresses in heat-treated materials. Next, a plasticity theory was developed

The second part of the research work was directed at the development of a plasticity theory for fibrous laminates. The objective was to construct a phenomenological constitutive relation suitable for use in numerical solutions of geometrically complex problems in laminated structures. Attempts to find such a relation were made with several microstructural models of a composite lamina. Two different models were finally selected, one of them was used in a finite-element program. Certain problems involving localized yielding at holes in laminated plates were solved. The author concludes that

The essential conclusion derived from this work is that the fiber reinforcement strengthens the metal matrix considerably against ultimate failure, but it does not expand significantly the elastic deformation range of the matrix in the overall stress space. ~~Therefore,~~ the advantage derived from fiber reinforcement of metal matrices can be utilized only in the elastic-plastic deformation range of the composite. This opens the possibility of repeated cyclic plastic straining of the matrix in dynamic loading situations, and the prospect of low-cycle fatigue failure if the loading range is not limited by the requirement that the matrix must shake down and thus resume an elastic deformation mode.

used

(10)